GREENFLATION:
THE COST OF THE GREEN-TRANSITION IN SMALL OPEN ECONOMIES

Preliminary and Incomplete[*]

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Abstract

We propose a new model of a small open economy with efficient energy use to investigate the inflationary dynamics along the green transition. The model incorporates the production of green energy that substitutes exogenous brown energy sources in production. Production is characterized by substitutability between the resource and other inputs that firms can alter though directed input-saving technical change. We investigate the dynamics of the green transition induced by either exogenous increases of brown energy prices and/or policy changes in the brown energy taxation; green subsidies and green public investment. Increases in brown energy prices and taxes decrease the usage of brown energy but do not expand significantly the green sector, they simply improve energy efficiency use, surging firm's marginal costs leading to greenflation and output losses. Green subsidies and public investment effectively increase the usage of green energy but imply a slower transition with no significant output and inflation costs and but with no improvements in efficient energy usage. The systematic reaction of monetary policy affects the transitional inflation dynamics.

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1 Introduction

Climate change is a fact and modern economies need to consider options for growth and development that reconsider the use of non-renewable resources and fossil-based energy. Avoiding introducing environmentally-friendly changes is costly in natural disasters, global warming, and the environment's deterioration. However, the transition from fossil-based production into a green economy is also economically costly.

In this paper, we study the inflationary process derived from the adoption of green energy. Considering the dynamic of prices and inflation is of first order for the Green transition. Along the transition there are changes in relative prices and in the aggregate price level. The transition is characterized by energy price increases that impact the marginal costs. This increase in marginal costs shape the adoption of technology and energy efficiency along the transition. However, on top of this, the increase in marginal costs impacts on the prices of consumption goods triggering substitution and wealth effects on the side of the consumer and a response from monetary and fiscal policies that feedback on the firms' production and technology adoption decisions. This second channel has been overlooked by the literature.

We propose a new model of a small open economy with energy use to understand both short and long-run movements in macroeconomic aggregates. We extend the New Keynesian small open economy model by modeling green energy production and allowing green and brown energy to be substitutes in energy production. We also incorporate in our analysis the production function suggested in Hassler et al. (2021) and Hassler et al. (2022) which features low substitutability between energy and other inputs, for given technology factors in the short-run, but significantly higher substitutability over longer periods when firms change factors´ efficiency dynamics through directed input-saving technical change. Our model captures the main features of Emerging Economies: these are economies subject to financial constraints that are represented by a positive premium of external debt in our framework and take international prices and risk free rates as given. To keep the model simple, we assume a domestic endowment supply of

brown energy, a type of energy that many emerging markets also produce.

We calibrate the model to the Chilean economy. We compute transitional dynamics for different cases. Starting from the initial steady state, we assume a 60 years' transition that ends with a) a 40% increase in brown energy prices. The positive trend in the price of brown energy is compatible with a resource constraint of fossil resources in the rest of the world that the small open economy takes as given.[1] The persistent price increase eventually drives the economy to a new steady state with a higher share of green energy use. In the short run the persistent increases in brown energy prices pushes marginal costs upwards. Given that agents foresee the increases in brown energy, firms accumulate more green capital and decrease smoothly the usage of brown energy, leading to a smooth increase in the ratio of green over brown energy. However, in the short and medium-run, the green transition induced by increases in energy prices implies surges in both brown and green energy prices. This, that initially affects only relative prices, results in a surge in inflation that smooths out gradually as the firms allocate more researchers to efficient energy usage increasing its productivity and lowering the price of green energy that ends up in a lower long-run level. The short-run dynamics of the economy resemble those of a sudden stop. Quantitatively increasing the ratio of green to brown energy from 0.13 to 0.21% in the new steady state implies a surge in inflation in the first two years that is contained and a substantial and persistent output fall. Hence, our analysis suggests that a green transition triggered by persistent increases in brown energy prices induces greenflation the first few years which is quantitatively contained, but the output costs are persistent and considerable. We show that monetary policy can affect the trade-off between output and inflation losses in the short-run of the transition, but cannot moderate substantially the output losses.

Given the inefficiency of monetary policy in moderating the output losses, we turn to study the role of fiscal policy. We next investigate how fiscal policy changes can induce transitional dynamics towards a greener economy. We investigate three scenarios a) increases in carbon taxes;

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[1]Hassler et al. (2022) assume that brown energy resources are scarce in the world economy. The positive trend in the price of brown energy should be compatible with such a resource constraint.

b) increases in green subsidies and c) investment in green capital infrastructure. For the sake of comparability, we implement policy changes that result to the same increase in the ratio of green to brown energy in the new steady state. Carbon taxes can accelerate the green transition but come at the cost of further inflationary pressures and output losses in the short and medium run. Subsidies and public investment in green capital instead have the potential of accelerating the green transition without generating inflationary pressures and output costs but in that case the pace of the transition is slower. Moreover, from an environmentalist point of view, taxes are preferable to subsidies and public green investment as these types of policies do not crowd out significantly the usage of brown energy.

Our focus on greenflation comes from a policy motivation. The inflationary cost of the transition has worried policymakers for a long time as Isabel Schnabel, the ECB executive responsible for market operations, said in a press release to the Financial Times: the planned transition away from fossil fuels to a greener low-carbon economy "poses measurable upside risks to our baseline projection of inflation over the medium term." She added that policies to tackle climate change, such as a carbon tax and measures to compensate poorer households for higher energy costs, are increasing inflationary pressures in the Euro Area. We also focus the analysis on emerging economies where these effects may be more substantial and which have traditionally operated in environments with pro-cyclical government spending, debt intolerance, and financing based on the inflation tax. Also, the transition might imply costs that alter the competitiveness of emerging economies, typically small open economies that are more frequently exposed to increased input costs for energy and other resources. Environmental regulation typically imposes constraints on markets that restrict the options available to firms that must decrease their profits or increase their prices. Hence, it is crucial to evaluate the price pass through during this transition and its potential beneficial effects on energy prices in the long run.

Starting from Kilian (2008), many existing studies evaluate the macroeconomic effects of energy price shocks. However, most of the analysis is typically limited to evidence gathered from short-

run national or cross-sectional studies and concerns shocks that relate to the price of oil that originate from demand or supply forces and not to economic transformation. Instead, one might be interested in assessing if an economy's vulnerability and resilience to shocks improve with economic development, as analyzed in van de Ven and Fouquet (2017), or actually how the macroeconomy is affected by economic transformation. The current analysis aims at understanding the transitional dynamics of green transformation and how these interact with monetary policy in emerging markets.

Relative to the existing models of the environmental literature as in Nordhaus (2008), Heutel (2012), Fischer and Springborn (2011), among others, we combine the environmental component with a standard general equilibrium model, what is by now tagged as a DSGE-E model (See e.g., Carattini et al. (2021) among others). Similar to Annicchiarico and Di Dio (2015) and Annicchiarico and Di Dio (2017), we add nominal frictions as in the New Keynesian literature. Our model differs from the existing models in several dimensions. We model the production of energy in the green sector and assume that the final good is produced using energy from both sectors and capital and labor inputs. Moreover, we assume that households invest in capital in the green energy sector that is combined with land to produce green energy. In contrast with the existing literature we do not assume any negative externalities in the use of brown energy apart from the fact that this energy source is exhaustible and its price reflects this constraint. Moreover, we also explicitly assume that the price of brown energy is affected by the country's economic conditions though the nominal exchange rate, which makes the energy usage in these countries more volatile and susceptible to different economic shocks.

The rest of the paper is organized as follows: Section 2 presents some motivating facts for the analysis. Section 3 presents the model and section 4 discusses the calibration and solution method employed. Section 5 collects the green transition dynamics and discusses different policy experiments and the last section concludes.

2 Clean energy, policies and inflationary pressures

Most emerging economies are lagging behind in the adoption of clean sources of energy when compared to Developed Economies. Figure 1 shows the consumption of renewable and non-renewable energy for the world, Latin America, and two particular LA economies (Brazil and Mexico) and Sweden and Norway, who are leading the adoption of clean energy.
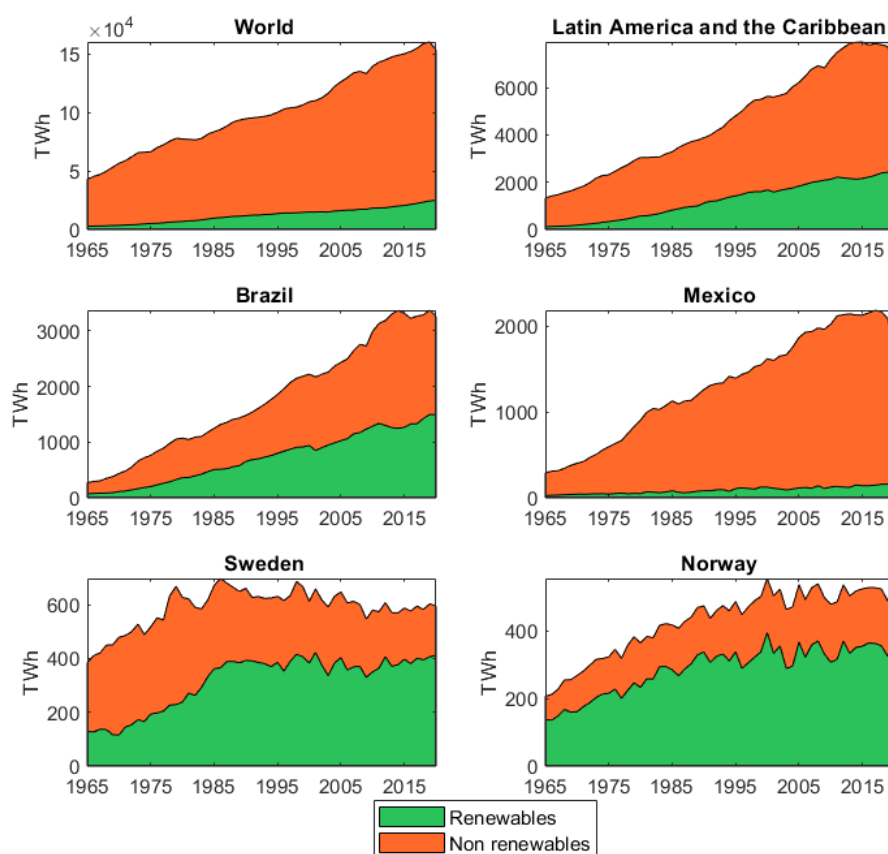

Figure 1: Renewable versus Non-renewable energy consumption

Note: Primary energy consumption in terawatt-hours (TWh). Source: BP Statistical Review of World Energy. 'Renewables' includes Solar, Wind, Hydropower, Nuclear, Biofuels, geothermal, biomass, and waste energy. 'Non renewables' includes oil, coal and gas.

Although a clear positive trend in the usage of green clean energy is apparent in all countries, there is a large gap between the share of renewable energy used among countries. For example, in Sweden and Norway who started the transition to clear energy over 60 years ago, renewable

energy accounts for 2/3 of total energy consumed. In Latin American economies this share is much smaller and bears significant heterogeneity: Brazil has clearly already started to move in the green transition, while Mexico has not.

In line with the relatively lower adoption of green energy in low developed economies, Figure 2 shows that these economies also have not invested in developing the installed capacity for renewable energy use over the last 20 years. Indeed, Latin-America and the Caribbean, Africa and, naturally, the Middle East have not increased their installed renewable energy capacity since the 2000, in contrast with countries in the European and Asian continent[2].
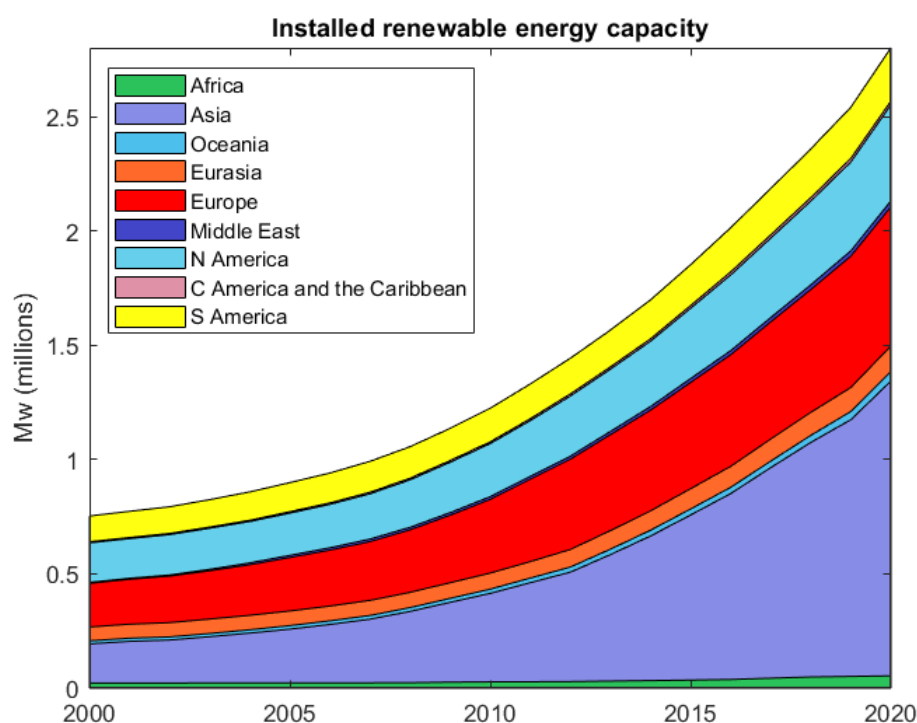

Figure 2: Installed renewable energy capacity.

Source: IRENA (2021), Renewable Capacity Statistics 2021; IRENA (2020), Renewable Energy Statistics 2020, The International Renewable Energy Agency, Abu Dhabi. Data in electricity capacity (MW).

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[2]Even within the European countries, there is a lot of diversity in renewable energy adoption. According to Eurostat, Sweden, Finland and Latvia are front runners in the green transition, while countries like Poland, Ireland, Hungary and Belgium are lagging very much behind. The same is true in Asia. Asia's installed renewable energy capacity almost tripled between 2009 and 2018. The growth is primarily led by China with India being the second largest renewable energy producer in Asia, while South Korea lags behind in clean energy adoption.

Hence, the evidence suggests that the green transition may imply challenges for some middle and low income economies in the short run. If these economies want to start the green energy transition they may encounter bottlenecks due to a higher demand of green energy in the presence of low renewable energy capacity, which, in turn may introduce inflationary pressures in the short run. To boost the transition, these economies, need to allocate resources to the exploitation of green technology and build the required capacity. This is going to imply higher costs in the short run and inducing a change in the use of non-renewable energy towards renewable energy sources will, in the absence of the right level of capacity, imply high costs, i.e. short run increases in the price of energy.
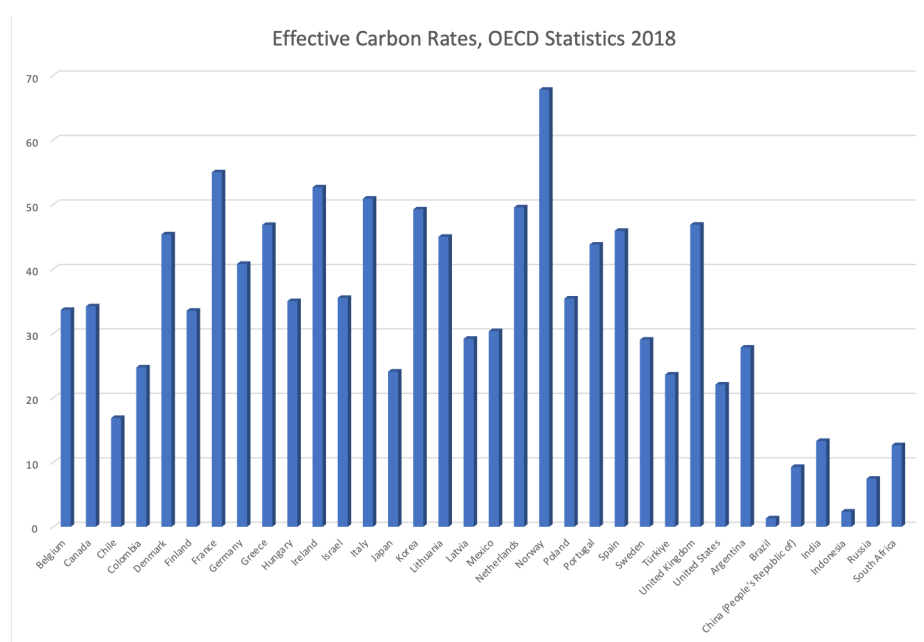
Figure 3: Carbon taxes

This is not the only potential driver of higher inflation due to the energy transition. A second reason for energy price increases during the transition is that economies will need to tackle the transition using fiscal and monetary measures. Figure 3 plots effective carbon tax rates in different countries according to OECD estimates in 2018 [3].Notice that the measure of comparison

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[3]OECD Effective Carbon Rates measures carbon pricing of CO2-emissions from energy use in 44 OECD and G20 countries, covering 80% of world emissions.

is 60 euros per metric ton of CO2-equivalent. EUR 60 is a midpoint estimate for carbon costs in 2020, and a low-end estimate for 2030. Pricing all emissions at least at EUR 60 in 2018 shows that a country is on a good track to reach the goals of the Paris Agreement to decarbonise by mid-century economically. Emerging economies such as Brazil, Chile, India and Turkey lag very much behind from this target, while in 2018 only Switzerland, Luxembourg (not shown in the graph for ease of exposition) and Norway reached a CPS_60 of close to 70%. Introducing further carbon taxation to promote the use of green energy will imply increases in the price of polluting energy, another source of inflation in the short run.

The evidence presented in this section suggest that some emerging economies loiter both in investments in renewable energy as well as policies to accelerate the green transition countries and procrastinate the transition. In the analysis that follows we try to assess quantitatively the real and nominal costs of transition for such economies and the impact of tax/subsidy and other government policies to promote the green transition in those economies.

3 Model

Our model is a version of small open economy New-Keynesian model with directed technology change and production of green and brown energy. The domestic economy is populated by households, final home good producers, intermediate goods producers, producers of green energy and a government that determines fiscal and monetary policies. In turn, the rest of the world determines a demand for home exports and provide imports of final goods and brown energy fully elastically at internationally given prices and buys/sells a risk-free asset. In the remainder of this section we describe each of the sectors in detail.

3.1 Households

The representative household in the domestic economy chooses consumption c_t, labor h_t, assets and two types of investment: investment in capital goods i_t and investment in green technol-

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ogy i_t^G. The investment in green technology adds to the green capital stock, s_{t+1}^G which evolves according to the following law of motion:

$$s_{t+1}^G = (1 - \delta) s_t^G + \Phi_s(s_{t+1}^G, s_t^G)s_t^G + i_t^G \tag{1}$$

Capital k_t follows a standard law of motion:

$$k_{t+1} = (1 - \delta) k_t + \Phi_k(k_{t+1}, k_t)k_t + i_t \tag{2}$$

Parameter δ represents a constant depreciation rate that we assume is the same in both specific capital stocks. Similarly, both capital stocks are subject to adjustment costs represented by function Φ_i, for $i = S, K$.

On top of investing in capital and green technology, the household can save in two different assets: a domestic public bond B_{t+1} that pays a nominal return R_{t-1} after one period, or a foreign bond B_{t+1}^*, with return $R_{t-1}^* \Phi_t^A(A_t^f)$, in foreign currency. The bonds are nominal, where $b_{t+1} = \frac{B_{t+1}}{P_t}$, $b_{t+1}^* = \frac{B_{t+1}^*}{P_t^*}$. In addition, the representative agent pays lump-sum taxes τ_t to the government, and receives transfers from the firms in the economy, Γ_t.

The household consumption c_t is a bundle composed of domestic and foreign goods ($c_{H,t}$ and $c_{F,t}$ respectively). The aggregation is given by:

$$c_t = \left[(1 - \chi)^{\frac{1}{\theta}} c_{H,t}^{\frac{\theta-1}{\theta}} + \chi^{\frac{1}{\theta}} c_{F,t}^{\frac{\theta-1}{\theta}} \right]^{\frac{\theta}{\theta-1}} \tag{3}$$

and their prices are $P_{H,t}$ and $P_{F,t}$. The optimal demand for domestic and foreign goods is:

$$c_{H,t} = (1 - \chi) \left(\frac{P_{H,t}}{P_t} \right)^{-\theta} c_t$$

and

$$c_{F,t} = \chi \left(\frac{P_{F,t}}{P_t} \right)^{-\theta} c_t$$

where P_t is the CPI in the domestic country, given by:

$$P_t = \left[(1 - \chi) P_{H,t}^{1-\theta} + \chi P_{F,t}^{1-\theta} \right]^{\frac{1}{1-\theta}} \tag{4}$$

The households offers inelastically a fixed number of hours, $\bar{h}$, to the firms.[4] Its intertemporal optimization problem consists in choosing, for all t, c_t, B_{t+1}, B_{t+1}^*, i_t^G, i_t, s_{t+1}^G, k_{t+1} to solve:

$$\max \mathbb{E}_0 \sum_{t=0}^{\infty} \beta^t U(c_t)$$

s.t.

$$i_t^G + i_t + c_t + \frac{B_{t+1}}{P_t} + FX_t \frac{B_{t+1}^*}{P_t} = \dots$$

$$\dots \frac{B_t}{P_t} R_{t-1} + FX_t \frac{B_t^*}{P_t} R_{t-1}^* \Phi_t^A(\tilde{A}_t^f) + w_t \bar{h} + \frac{R_t^k}{P_t} k_t + \frac{R_t^G}{P_t} s_t^G + \Gamma_t - \tau_t$$

$$s_{t+1}^G = (1 - \delta) s_t^G + \Phi_s(s_{t+1}^G, s_t^G) s_t^G + i_t^G$$

$$k_{t+1} = (1 - \delta) k_t + \Phi_k(k_{t+1}, k_t) k_t + i_t$$

where, FX_t is the nominal exchange rate, and $\Phi_t^A(\tilde{A}_t^f)$ is a debt-elastic interest rate premium given by:

$$\Phi_t^A(\tilde{A}_t^f) = \exp \left\{ -\phi^A \left[\tilde{A}_t^f + \mu_t^f \right] \right\}$$

where μ_t^f is a risk premium and $\tilde{A}_t^f$ is the real outstanding foreign debt in domestic currency, as

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[4]The model with a labor supply choice does not provide the analysis with additional incentives and it is harder to solve numerically.

in Justiniano and Preston (2010):

$$\tilde{A}_t^f = \frac{FX_t}{P_t\bar{Y}}\tilde{B}_t^*.$$

This implies

$$\tilde{A}_t^f = \frac{FX_t P_{t-1}^* P_t^*}{P_t^* P_t \bar{Y}}\frac{\tilde{B}_t^*}{P_{t-1}^*} = \frac{rer_t}{\pi_t^* \bar{Y}}\tilde{b}_t^*$$

and $\bar{Y}$ is the domestic output at the steady state. We present the Household's optimality conditions in the appendix.

3.2 Domestic final good firms

A representative firm produces the domestic final good $y_{H,t}$ from varieties $y_{H,i}$, for i $\in [0,1]$.

$$y_{H,t} = \left[\int_0^1 y_{H,i,t}^{\frac{\varepsilon-1}{\varepsilon}}di\right]^{\frac{\varepsilon}{\varepsilon-1}}$$

ε is the elasticity of substitution between varieties. The optimization problem of the representative firm is the following:

$$\max_{y_t,\{y_{H,i,t}\}_{i\in[0,1]}} P_{H,t}y_{H,t} - \int_0^1 P_{H,i,t}y_{H,i,t}di$$

$$\text{s.t } y_{H,t} = \left[\int_0^1 y_{H,i,t}^{\frac{\varepsilon-1}{\varepsilon}}di\right]^{\frac{\varepsilon}{\varepsilon-1}}$$

And the optimal demand function for variety i is given by the following expression:

$$y_{H,i,t} = y_{H,t}\left(\frac{P_{H,i,t}}{P_{H,t}}\right)^{-\varepsilon} \tag{5}$$

3.3 Intermediate-good firms

Each firm in the intermediate-goods sector produces a variety $y_{H,i,t}$ in monopolistic competition, facing a downward demand function $a_{H,i,t}$. The technology for producing variety i uses fixed labor $\bar{h}_i$, physical capital $k_{i,t}$ and energy $e_{i,t}$ as productive inputs. Following Hassler et al. (2021) and Hassler et al. (2022), we assume the following technology:

$$y_{H,i,t} = \left[\left(A_t k_{i,t}^{\alpha} \bar{h}_i^{(1-\alpha)} \right)^{\frac{\epsilon-1}{\epsilon}} + \left(A_{e,t} e_{i,t} \right)^{\frac{\epsilon-1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}}$$

A_t and A_t^e are input-augmenting productivity factors, that are non-stationary. To account for changes in A and A_e, we assume that each firm disposes a fixed stock of researchers, n (equal to one), that can be allocated to improve the productivity of capital/labor and/or energy services as in Hassler et al. (2022). Relative to the former authors we assume that n is endogenous and determined at the firm level and use it as a way for the firms in the domestic economy to adjust to changes in the relative supply of energy. Fixing the stock of researchers dedicated to improve the efficiency in the energy versus the capital/labor services is actually fixing the relative movements of the two trends[5]. More precisely, the proportion of researches in each sector affects the corresponding growth rates of productivity $A_{e,t}$, A_t, in the following fashion:

$$g_t^A = \frac{A_t}{A_{t-1}} = 1 + B n_t^{\phi}$$

$$g_t^{Ae} = \frac{A_{e,t}}{A_{e,t-1}} = 1 + B_e (1 - n_t)^{\phi}$$

As it is clearly demonstrated by the determinants of the two growth rates , firms face a trade-off in the allocation of researchers. A rise in R&D in one sector increases its productivity growth rate, at the cost of decreasing the one in the other sector. We assume that the firms optimally choose n_t to balance this trade off. Notice that a key feature of the production function is the

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[5]Obviously, a single firm cannot change the economy's trends. Given that all firms behave symmetrically in equilibrium, we find this to be an innocuous assumption.

substitution elasticity parameter between traditional inputs and energy. Although we can assume this elasticity to be near zero in the short run , i.e., almost Leontief, directed input-saving technical change can alter this elasticity at longer horizons. That is, by choosing n, the producer can move resources from A_t to $A_{e,t}$ increasing the intensity (or efficiency) of use of energy compared to labor and capital, allowing for a medium-run increasing resource use.

With regards to the energy used in the intermediate production sector, we assume that it is an aggregate of the polluting ($e_{i,t}^B$) and clean energy ($e_{i,t}^G$), produced by "brown" and "green" energetic sectors, respectively. It is given by

$$e_{i,t} = \left[(1-\zeta) \left(e_{i,t}^G \right)^{\xi} + \zeta \left(e_{i,t}^B \right)^{\xi} \right]^{\frac{1}{\xi}} \tag{6}$$

where ζ characterizes the relative importance of brown over total energy resources and ξ the elasticity of substitution between brown and green energy.

The optimization problem of firm i consists in choosing the allocation of researchers n_t, price $P_{H,i,t}$, and inputs of production $e_{i,t}^B$, $e_{i,t}^G$, taking as given the demand function $a_{i,H,t}$, given by (5), and input prices P_t^G, P_t^B, W_t. When the firm changes the variety price, it has to pay an adjustment cost given by:

$$\Phi^{PH}(.) = P_{H,t} \frac{\kappa_{PH}}{2} \left(\frac{P_{H,i,t}}{P_{H,i,t-1}} - \bar{\pi}_H \right)^2 a_{H,t}$$

in nominal terms, as in Rotemberg (1982). Additionally, the firm has to pay a government tax τ^e proportional to the purchases of brown energy $P_t^B e_t^B$, and receives a subsidy s proportional to purchases of green energy $P_t^G e_t^G$.

The firm's optimization problem, in nominal terms, is the following:

$$\max \mathbb{E}_0 \left\{ \sum_{t=0}^{\infty} \beta^t \frac{\lambda_t}{\lambda_0} \left[P_{H,t} \left(\frac{P_{H,i,t}}{P_{H,t}} \right)^{-\varepsilon} a_{H,t} - P_t^G e_{i,t}^G (1-s) - P_t^B e_{i,t}^B (1+\tau^e) - W_t \bar{h}_i - P_{H,t} - R_t^k k_t - \right. \right.$$

$$\left. \left. \frac{\kappa_{PH}}{2} \left(\frac{P_{H,i,t}}{P_{H,i,t-1}} - \bar{\pi}_H \right)^2 a_{H,t} + MC_t \left(F(e_{i,t}, h_{i,t}) - \left(\frac{P_{H,i,t}}{P_{H,t}} \right)^{-\varepsilon} a_{H,t} \right) \right] \right\}$$

Where λ_t is the discount factor of the firm that coincides with the Lagrange multiplier of the consumer's problem. τ^e and s represent green fiscal instruments. τ^e is a tax on brown energy consumption, and s is a subsidy on purchases of green energy. We solve for a symmetric equilibrium, where all intermediate firms take the same decisions. The optimality conditions are described in the Appendix.

The optimal decision for n_t is given by:

$$\left(A_t k_t^\alpha h^{1-\alpha} \right)^{\frac{\epsilon-1}{\epsilon}} \frac{A_{t-1}}{A_t} B\phi n_t^{\phi-1} = e^{\frac{\epsilon-1}{\epsilon}} \frac{A_{t-1}^e}{A_t^e} B_e \phi \left(1 - n_t \right)^{\phi-1}$$

and the optimal pricing decision results to:

$$\pi_{H,t} \left(\pi_{H,t} - \bar{\pi}_H \right) = \beta \mathbb{E}_t \left[\frac{\lambda_{t+1}}{\lambda_t} \pi_{H,t+1} \left(\pi_{H,t+1} - \bar{\pi}_H \right) \frac{a_{H,t+1}}{a_{H,t}} \right] + \frac{\varepsilon}{\kappa_{PH}} \left(\frac{mc_t}{p_{H,t}} - \frac{\varepsilon - 1}{\varepsilon} \right) \tag{7}$$

which is the New Keynesian Phillips Curve, where $p_{H,t} = \frac{P_{H,t}}{P_t}$ is the relative price of domestic produced goods with respect to the price level in the economy and and real marginal cost is $mc_t = \frac{MC_t}{P_t}$. Real profits are given by:

$$\Gamma_t^I = p_{H,t} a_{H,t} - P_t^G e_{i,t}^G (1-s) - P_t^B e_{i,t}^B (1+\tau^e) - w_t \bar{h} - R_t^k k_t - \frac{\kappa_{PH}}{2} \left(\frac{P_{H,i,t}}{P_{H,i,t-1}} - \bar{\pi}_H \right)^2 a_{H,t}$$

3.4 Energy sectors

3.4.1 Green energy production

Green energy is produced domestically combining specific green technology s_t^G, a stock of public capital $s_t^{G,P}$, and a factor that is in fixed limited supply, L, according to the following production function:

$$e_t^G = \Omega L^{1-\mu}[(1-\gamma)(s_t^G)^\omega + \gamma(s_t^{G,P})^\omega]^{(\mu/\omega)} \tag{8}$$

Where Ω_t denotes the level of productivity in the clean energy production, and $s_t^{G,P}$ is the level of green public capital, and parameters ω and γ, determine the elasticity of substitution between private and public stocks of green capital and the share of each in green energy production.

This sector does not choose the shock of public capital in the production. It solves a static optimization problem consisting in choosing how much green technology to rent s_t^G to maximize the period profits, taking prices P_t^G, R_t^G and technology as given. For simplicity, we assume the return on the fixed factor L is equal to zero:

$$\Gamma_t^G = P_t^G e_t^G - R_t^G s_t^G (1 - s^G)$$

3.4.2 Brown energy

The economy receives an endowment of brown energy, $e_t^{B,d}$, that we assume is traded internationally and can be exported or imported at international price $P_t^{B,*}$. Since e_t^B is the domestic demand of brown energy, the imports of brown energy, $e_t^{B,*}$, are given by:

$$e_t^{B,*} = e_t^B - e_t^{B,d}$$

We assume the law of one price holds for the brown energy market, and thus the domestic price

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of brown energy is the following:

$$P_t^B = FX_t P_t^{B,*}$$

From the previous expression, note that

$$\frac{P_t^B}{P_t} = \frac{FX_t P_t^{B,*} P_t^*}{P_t P_t^*}$$

or

$$p_t^B = rer_t p_t^{B,*}$$

We assume that the international price $p_t^{B,*}$ is an exogenous process.

3.5 Final goods imports

The economy imports foreign differentiated goods $y_{F,i,t}$, for which the law of one price holds. This means $P_{F,i,t} = FX_t P_{F,i,t}^*$. In addition, assuming a small open economy implies $P_{F,t}^* = P_t^*$. Integrating over all varieties, we obtain: $P_{F,t} = FX_t P_t^*$, that is the price level of imported goods. And dividing over the domestic price level, we get the real exchange rate:

$$p_{F,t} = rer_t = FX_t \frac{P_t^*}{P_t} \tag{9}$$

and the growth rate of the real exchange rate can be written as a function of the nominal exchange rate depreciation, domestic and foreign inflation rates:

$$g_t^{rer} = \frac{rer_t}{rer_{t-1}} = \frac{FX_t}{FX_{t-1}} \frac{\pi_t^*}{\pi_t} \tag{10}$$

where we assume that the foreign inflation rate π_t^* follows an AR(1) process.

3.6 Final goods exports

The foreign demand for domestically produced goods is given by the following expression:

$$c^*_{H,t} = \left(\frac{P^*_{H,t}}{P^*_t}\right)^{-\lambda} y^*_t$$

where λ is the elasticity of substitution of foreign and domestic goods, in the foreign economy, and it could be different from θ.

The processes for foreign output y^*_t and foreign inflation π^*_t are exogenous from the point of view of the small open economy.

3.7 Monetary Authority

The central bank sets the domestic interest rate R_t following a Taylor rule that depends on inflation and output deviations from their steady state value.

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R}\right)^{\rho_R} \left[\left(\frac{\pi_t}{\bar{\pi}}\right)^{\phi_\pi} \left(\frac{y_t}{y}\right)^{\phi_y}\right]^{1-\rho_R} \tag{11}$$

3.8 Fiscal Authority

The fiscal authority satisfies the following period budget constraint:

$$\tau_t + \tau^e p^B_t e^B_t + b_{t+1} = sp^G_t e^G_t + \frac{b_t}{\pi_t} R_{t-1} + i^{pub}_t \tag{12}$$

b_{t+1} is debt with one-period maturity, purchased by domestic households. τ_t are lump-sum taxes to the households, that follow a fiscal rule:

$$\tau_t - \tau^* = \phi_\tau \left(b_t - \bar{b}\right) + \sigma^\tau \epsilon^\tau_t$$

where τ^* is a the steady state value of this tax, ϵ_t^τ is a fiscal shock, and ϕ_τ is the elasticity of taxes to debt deviations from the steady state. When this elasticity is high enough, the fiscal authority is adjusting taxes to ensure debt sustainability.

i_t^{pub} is public investment, which we assume follows an exogenous process.

3.9 Aggregation

Aggregating all domestic and foreign agents we derive the market clearing condition for home produced goods and the NIPA equation together with the definition of net exports. These expressions are as follows

$$y_{H,t} = (1 - \chi)p_{h,t}^{-\theta}\left(c_t + i_t + s_t^G + i_t^{pub}\right) + c_{H,t}^*$$

$$p_{H,t}y_{H,t} = c_t + i_t + i_t^G + i_t^{pub} + \frac{\kappa_P}{2}\left(\pi_t^H - \bar{\pi}_t^H\right)^2 p_{H,t}y_{H,t} + nx_t + p_t^B e_t^{B,*}$$

$$nx_t = \frac{FX_t}{P_t}P_t^*\frac{B_{t+1}^*}{P_t^*} - \frac{FX_t}{P_t}P_t^*\frac{B_t^*}{P_t^*}R_{t-1}^*\Psi^A\left(\tilde{A}_t^f\right)$$

Then

$$nx_t = rer_t b_{t+1}^* - rer_t\frac{b_t^*}{\pi_t^*}R_{t-1}^*\Psi^A\left(\tilde{A}_t^f\right)$$

Transfers to households are given by:

$$\Gamma_t = \Gamma_t^I + \Gamma_t^G$$

3.10 Balance growth path assumptions

As mentioned earlier, the directed technical change affects the long run energy share and growth in the economy (See also Hassler et al. (2021)). In particular, define X_{t-1} as the output trend at

period t, at which $y_{H,t}$ grows. We define:

$$X_t = A_t k_t^\alpha \tag{13}$$

such that:

$$g_t = \frac{X_t}{X_{t-1}} = \frac{A_t k_t^\alpha}{X_{t-1}^{1-\alpha} X_{t-1}^\alpha} = \tilde{A}_t \tilde{k}_t^\alpha \tag{14}$$

is the growth rate of the economy. Since the stock of capital's trend is X_{t-1}, its productivity factor A_t grows at $X_{t-1}^{1-\alpha}$. $\tilde{A}_t$ and $\tilde{k}_t$ are the stationarized counterparts of A_t and k_t.

To have a balance growth path, given the functional form of the production function, we need the two additive parts of it to grow at the same rate. It means that we need:

$$X_{t-1} = X_{t-1}^{Ae} X_{t-1}^e$$

and from 6:

$$X_t^e = X_t^{eG} = X_t^{eB}$$

meaning all energy sources grow at the same rate, for all t.

Then, from the production function of green energy, we get the following condition:

$$X_{t-1}^{eG} = X_{t-1}^\mu$$

Hence,

$$X_{t-1}^{eB} = X_{t-1}^e = X_{t-1}^\mu$$

and

$$X_{t-1}^{Ae} = X_{t-1}^{1-\mu}$$

Finally, from the first order condition of intermediate producers with respect to energy inputs,

we get that prices p_t^G and p_t^B grow at: $X_{t-1}^{1-\mu}$.

In the appendix, we present the complete set of stationarized equations.

4 Calibration and solution

4.1 Numerical implementation

We solve the model for perfect foresight solution. Our calibration strategy intends to target business cycle first and second order moments on national accounts and energy production and use for Mexico.

4.2 Functional forms

Utility function:

$$U = \frac{c_t^{1-\sigma}}{1-\sigma}$$

Capital adjustment costs

$$\Phi\left(\frac{k_{t+1}}{k_t}\right) = \frac{\kappa_K}{2}\left(\frac{k_{t+1}}{k_t} - \bar{g}\right)^2$$

We assume a similar form for the adjustment costs for green capital:

$$\Phi\left(\frac{s_{t+1}^G}{s_t^G}\right) = \frac{\kappa_S}{2}\left(\frac{s_{t+1}^G}{s_t^G} - \bar{g}\right)^2$$

4.3 Calibration

We calibrate the model matching first and second moments for the economy of Chile from the period 1960:2019. The frequency is annual and Table 1 reports the parameter values we use in our numerical exercise. In the steady state, according to the Euler equation, the discount factor relates to the values of the intertemporal elasticity of substitution that we set equal to one, the average growth rate that according to the data average is 1.025, the average inflation rate which equals 4

percent and the average nominal rate which is 3 percent. We set $\beta = 0.995$ which is consistent with a slightly positive interest rate in the steady state. Following Justiniano and Preston (2010), we set the elasticity of substitution between domestic and foreign goods equal to 0.85 and the share of foreign goods in consumption to 0.24. The elasticity between domestic varieties is set so that the steady state markup is 11 percent. The depreciation rates are set equal for both types of capital to target an annual depreciation rate of 12%. The physical adjustment costs are set to match the volatility of investment over output in the data. We set the effective capital share at 0.26.

We set the elasticity of substitution between physical capital and energy to 0.35, which implies that the two inputs are complements in production, and the share of brown energy in the total energy production to 0.53. The substitution of energy inputs in the energy production is set to 0.67 according to the estimates of Papageorgiou et al. (2017), assuming that the two energy inputs are substitutes. We also assume that the share of effective green capital in the production of green energy is 30% and normalize land in the production to equal 0.1, which is compatible with having the share of the green investment to capital in the steady state equal to the data average of 0.3 percent. The coefficients of the production of technical change of researchers are similar to the ones assumed by Hassler et al. (2021). Finally, the adjustment costs of prices are set equal to 30. The value of κ_P determines the degree of nominal rigidity. One can relate this value to the average price contract length by exploiting the relationship between the log-linearized NK Phillips curve in the Calvo model and the one implied by the Rotemberg model assumed in the current paper. In particular, the slope of the Phillips curve with respect to real marginal costs is equal to ϵ/κ_P, while the corresponding value in the Calvo model is $[(1 - \Psi)(1 - \Psi\beta)/\Psi]$ where $1/(1 - \Psi)$ is the average contract length. According to this relationship, the value of κ_P we chose corresponds roughly to an average contract length of one year.

The parameterization of the Taylor coefficients is very standard. In the baseline calibration all policy parameters are set to zero apart from the tax response to debt that we set equal to 0.17.

Table 1: Parameter Values

β	Discount factor	0.995
σ	CES elasticity in utility	1.00
g	Average growth rate	1.025
π	Average inflation	1.04
R^*	Average risk free rate	1.03
θ	Substitution between home and foreign goods in consumption	0.85
λ	Foreign demand coefficient	0.85
χ	Share foreign goods in consumption	0.24
ϵ_p	Elasticity between varieties	10.0
δ_K,δ_S	Depreciation rate of physical and green stock of capital	0.12
κ_K,κ_S	Adj. cost of phycical and green capital	0.005
α_A	Capital share	0.26
ϵ	Substitution between Energy and other factors	0.35
ζ	Share of brown energy	0.53
ξ	Substitution between energy inputs	0.67
Ω	Average Productivity of green technology $e_G/e = 11\%$	0.71
μ	Share of effective green capital in production of green energy	0.42
L	Land (Fixed factor)	0.10
ϕ_A	Spread coefficient, spread= 3%	0.005
B	Production function coefficient for researchers	0.030
ϕ_N	Production function coefficient for researchers	0.880
κ_P	Adj. cost of prices	30.00
ϕ_π	Interest rate response to inflation	1.500
ϕ_Y	Interest rate response to output	0.250
ρ_R	Interest rate smoothing parameter	0.85
τ^*	Average tax	0.17
ϕ_τ	Tax response to debt	0.10
$\frac{nx}{y}$	Target for net exports to GDP	0.012
$\frac{d}{y}$	Target debt to GDP ratio	0.60
γ	Share of Public investment in green energy production	0.40
ω	Elasticity of green public and private capital	0.1

Matching the data for Chile we assume that the country in the steady state has positive next exports and the debt to GDP ratio is set to 60 percent. Finally, we set the parameters for the production of green energy so that the share of public investment in green energy production is 40 percent and the elasticity of public and private green capital equals 0.1.

5 Transitional Dynamics

For the transitional dynamics we focus on a perfect foresight model as our interest is in the long run dynamics for which short run uncertainty is not needed. We assume the economy is in equilibrium (in the equilibrium consistent with steady state) before period 1. Starting at this initial condition we simulate a Green Transition where the economy is moving from low use of green energy to extensive use of it. Given that the economy is a perfect foresight one, the whole transition is known by the agents in the model since period 1.

Numerically, the solution of the model implies solving a set of nonlinear equations given by

$$f(y_2, y_1, y_0, u_1) = 0$$

$$\vdots$$

$$f(y_{t+1}, y_t, y_{t-1}, u_t) = 0$$

$$\vdots$$

$$f(y_{T+1}, y_T, y_{T-1}, u_T) = 0$$

for each endogenous variable for each period t. Here, $f(y_{t+1}, y_t, y_{t-1}, u_t)$ denotes the set of equations that characterizes the equilibrium, y_t is the vector of endogenous variables and u_t a vector of innovations that is perfectly known. The initial conditions are y_0 (initial steady state) and the terminal conditions are y_{T+1} (final steady state).

5.1 A transition induced by increases in brown energy prices

We first assume that the secular dynamics around the Green transition are driven by increases in brown energy prices determined in the rest of the world ($P^*_{B,t}$). To be precise, starting from the initial steady state, we assume a 60 year transition that ends with a 30% increase in brown energy prices. Figure 4 presents the transitional dynamics of the small open economy. The increase in the international price of brown energy accelerates the use of green energy and reduces the use of brown energy and the economy ends up in a new equilibrium where the use of brown energy is permanently reduced in favor of green energy usage. In the new steady state the ratio of green to brown energy increases by 40%. In the shorter run, the increase in the international price of brown energy drives up domestic brown energy prices and given the relatively low substitutability between brown and green energy in production also the price of green energy. This results in a surge in inflation in the short and medium run that smooths out gradually as the firms allocate more researchers to efficient energy usage increasing its productivity.

Given the reallocation of researchers along the transition, the productivity of traditional inputs slows down shortly and this discourages physical capital accumulation but as green energy becomes more efficiently used its path reverses in the medium run and the productivity of traditional factors increases as well in the medium run[6]. However, the complimentarity between energy and traditional inputs in the short run coupled with the slow dynamics in the energy accumulation and the increase in the price of brown energy render the green transition recessionary. In other words, since firms perfectly foresee long-term increases in brown prices, they adjust their production by decreasing traditional factors and in particular investment demand generating a recession in the short run. Actually, the dynamics of the economy resemble those of a sudden stop with output falling and net exports reverting in the short run.

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[6]Note that the picture depicts detrended productivity, A. Given its definition productivity cannot fall below one.
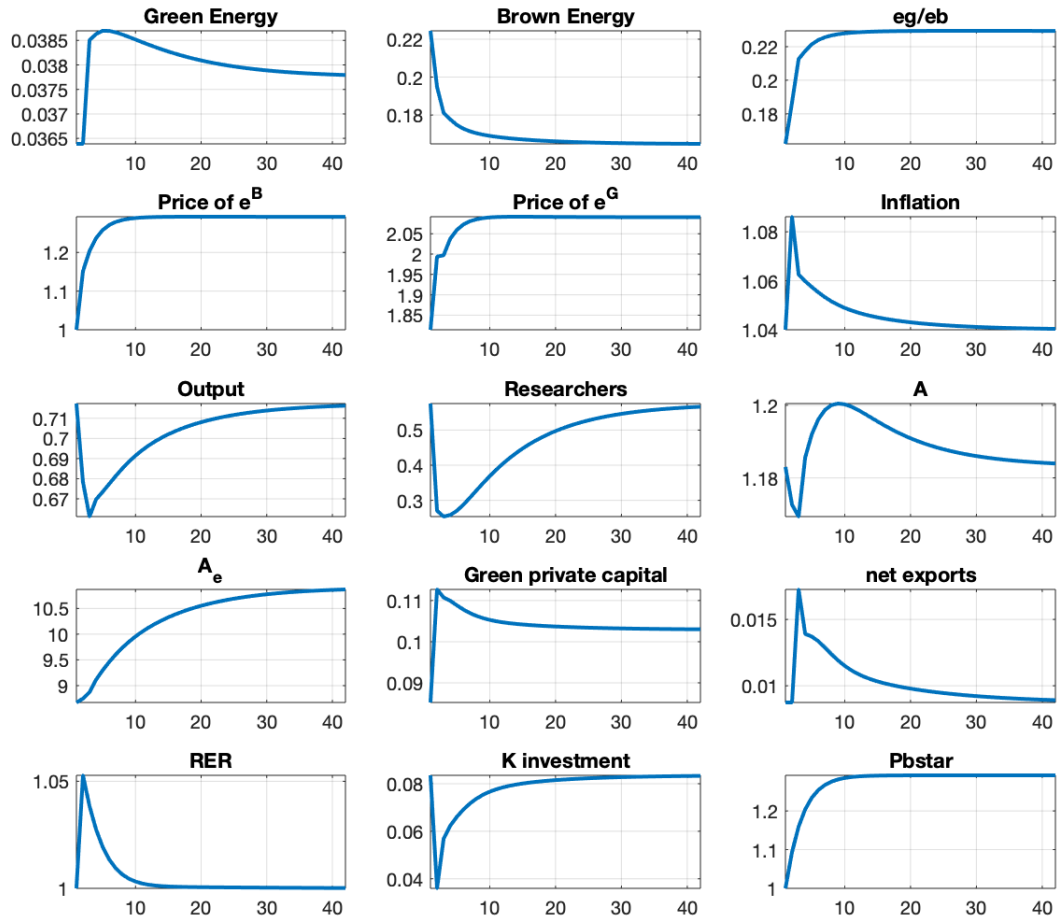
Figure 4: Transitional Dynamics: Increases in Brown Energy Prices

Quantitatively for a 40% increase in the ratio of green to brown energy, inflation increases at maximum in the second year from 4 to 8.6 percent and the maximum output fall is considerable (7.8% in the third year) and persistent. Hence, our analysis suggests that such transition induces "greenflation" the first few years and significant and persistent output losses. The effects of the shock on inflation are moderate because the negative demand effect from the fall in private investment moderates the inflationary consequences of the shock.

5.2   The role of supply and demand frictions

The macroeconomic dynamics of the green transition depend crucially on the frictions we have assumed in the demand and the supply side of the economy. Given that the model is one with sticky prices demand frictions in the short run will affect the transition while supply frictions also have a role in shaping firms responses in face of brown price changes. We investigate here how the major frictions affect the macroeconomic dynamics.

From the demand side we consider the role of price stickiness in shaping the transitional dynamics. Figure 5 plots the transitional dynamics for our benchmark economy in blue continuous lines and the dashed yellow lines correspond to the dynamics that would result in an economy that is otherwise identical to the benchmark economy except for a higher degree of price stickiness. Notice that changing the degree of price stickiness in the economy does not alter the two steady states relative to the benchmark economy but it affects the transitional dynamics. In the hypothetical economy price take on average more than two years to adjust. As a result, the demand channel in this economy is stronger. When agents foresee increases in carbon taxes they would like to increase consumption today in view of higher prices in the future, at the same the increased taxation of brown energy prices pushes up marginal costs. However, when prices are more sticky firms cannot react immediately to the rise in marginal costs and as a result the inflation responses are somewhat smaller and so are the maximum output losses along the transition. Increasing price rigidities in the economy, however, does not alter significantly the transitional dynamics and the changes in the short run dynamics are marginal.
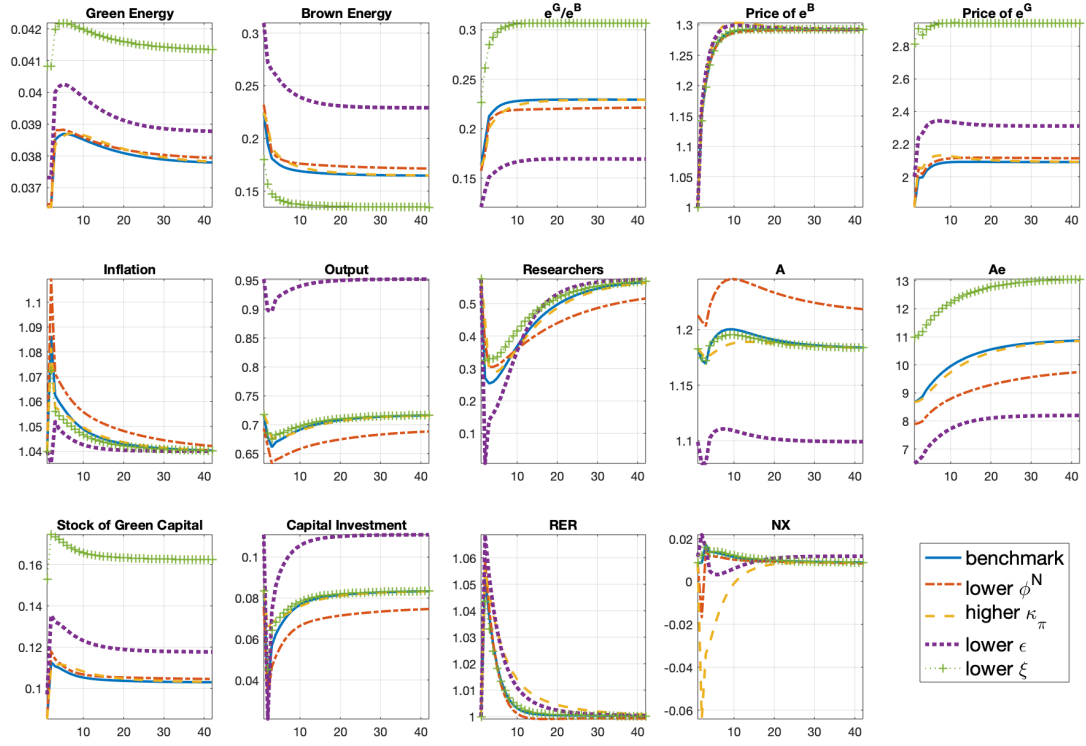
Figure 5: Transitional Dynamics: The role of frictions

From the supply side, we have assumed various frictions that could affect significantly the transitional dynamics, but also the initial and terminal steady states. We start by considering how rigidities in allocating researchers for improving traditional inputs' or energy's efficiency shape the transitional dynamics we have described in the benchmark economy. When we look at this case, we consider a lower ability of firms to move researchers in order to increase energy efficiency by decreasing parameter ϕ^N (we reduce ϕ^N to 0.8 in this case) . The transitional dynamics of the economy with lower ϕ^N is depicted with red dashed-dotted lines in Figure 5. Supply frictions play a crucial role for determining steady states and transitional dynamics. When firms cannot switch researchers through directed search easily, the economy reaches a steady state with a lower ratio of green to brown energy usage relative to the benchmark since the difficulty in re-allocating researchers translates in productivity differences that persist in the new steady state as

it is clearly shown in the dynamic path of A_e. Moreover, the increase in marginal costs from the higher brown energy prices becomes more costly in terms of both inflation and output. Not being able to increase efficiency firms reduce their supply and given the increased demand this leads to huge increases in inflation in the short run. Inflation increases from 4 to almost 12 percent in the short run and remains above 5 percent for almost 17 years and output falls by almost eight percent in the short run and remains persistently low for many years.

We next investigate how the assumed elasticity between traditional factors and energy affects the macroeconomic dynamics of the green transition. In the benchmark calibration we have assumed that $\epsilon = 0.35$, we now reduce $\epsilon = 0.1^7$. The case of lower ϵ is depicted with dotted purple lines in Figure 5. In the benchmark economy we assume traditional factors and energy to be complements in production with setting $\epsilon = 0.35$, by decreasing ϵ, we increase the complementariry between traditional factors and energy. The value of ϵ affects the steady states and the transitional dynamics. Lower values of ϵ imply a higher initial steady state value for output and brown energy and a lower initial steady state value of productivity A and A_e. Moreover, the fact that energy becomes a stronger complement to traditional factors implies that firms have to move much more resources towards R&D when the news of permanent increases in brown energy prices arrive in order to maintain production capacity. Although comparing is really hard given the changes in the steady states, the inflationary costs of the green transition in this economy are clearly lower. Firms' behavior complies with the intuition for the benchmark economy, they substitute for brown energy increasing the efficiency of energy usage as in the previous cases and the consumption of brown energy is reduced. However, the higher complementarity between traditional factors and energy reduces the surge in firm's marginal costs as the change in resources to R&D is more abrupt and dictates a faster reversal in production costs. Finally, we investigate how changes in the substitutability between green and brown energy in production affect the transitional dynamics. Again changing ξ alters also the steady state values of green

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[7]Hassler et al. (2021) assume $\epsilon = 0.02$. Given the change in the steady state values that this calibration implies, for ease of comparisons with our benchmark calibration we do not show the results of this alternative calibration in Figure 5. The intuition behind the results for lower values of ϵ holds even for very low values of this parameter.

energy and prices. However, it is safe to say that the value of ξ (here we assume that $\xi = 0.1$) does not affect significantly the macroeconomic losses in terms of output and inflation along the green transition.

Overall our sensitivity analysis suggests that it is important to take into account the idiosyncrasies of every economy when designing possible green transitions, as supply and demand frictions are important for shaping the transitional dynamics.

5.3   The role of monetary policy

Figure 4 clearly illustrates that along the transition monetary policy might face a trade off between inflation and output stabilization. Now days, the role of the monetary policy stance during the green transition is at the centre of academic and policy debates. In Figure 6 we repeat the baseline exercise by changing the stance of monetary policy. In the benchmark economy we have assumed a Taylor coefficient of inflation of 1.5 we reduce now this value to 1.05 (dashed yellow lines in Figure 6) and increase it to 5 (red dashed dotted lines in Figure 6). The monetary policy stance affects the transitional dynamics of inflation. That is, a stricter monetary policy stance shields the economy against inflation. However, this comes at a cost of higher short run losses for output.Relative to standard NK models in our model economy monetary policy affects also the incentives to accumulate green capital in the short run and monetary policy choices seem to be crucial for determining the external balance along the green transition. Still, a looser inflation targeting does not seem to bring gains in terms of output losses along the transition. Hence, we would conclude that in our small open economy targeting inflation could be beneficial for moderating greenflation but such policy would not affect almost at all real output losses along the transition and would not affect the transitional dynamics either.
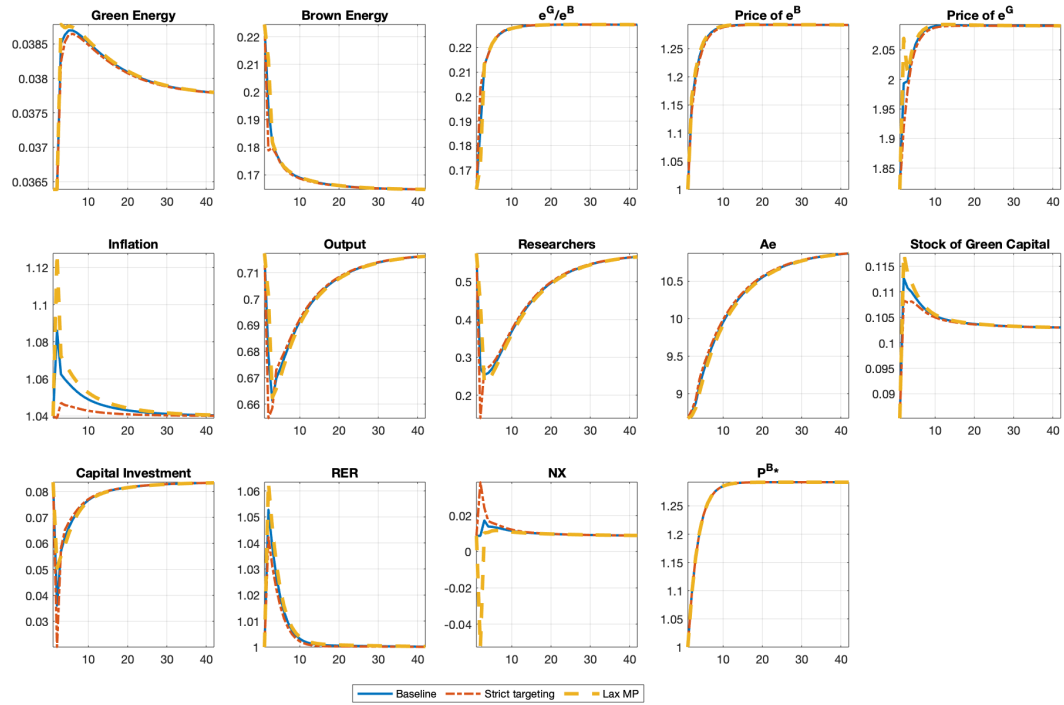
Figure 6: Transitional Dynamics: The role of monetary policy

5.4 The role of fiscal policy

We now present how fiscal policy can affect the green transition. To grasp a better understanding of the effects of fiscal policy we investigate each fiscal instrument separately and induce policy changes that result in a new steady state with the same increase in the green to brown energy ratio as the one induced by changes in brown energy prices. Hence, in the exercises that follow we keep the level of international brown energies fixed and change the fiscal instrument to induce a transition that resembles in terms of the ratio of green to brown energy the transition that results from permanent changes in the international brown energy prices.

5.4.1 Taxing the Brown Energy

In Figure 3 we have presented evidence pointing to substantial heterogeneity in the level of effective carbon taxes in emerging and developed economies. Since, carbon taxes, affect the price

of brown energy one would expect that they should equally affect the green transition. The red dotted lines in Figure 7 present the transition of the economy when brown taxes change from 10 in the initial steady state to 40 percent in the new steady state during a 60 year transition, while brown energy prices remain fix at their initial level.

Naturally, when the taxation of the brown energy increases this translates into increases in the intermediate firms' marginal costs that tend to push up inflation. At the same time increases in taxation should generate a negative wealth effect that decreases demand. On the supply side, firms try to move researchers in order to improve the efficiency of energy usage and substitute brown for green energy faster. This behavior decreases the demand for capital but increases the demand for green capital. Overall, domestic demand falls short of domestic supply and in order for the international markets to clear the real exchange rate depreciates raising also the price of brown energy, accelerating further the transition. Yet, the policy has substantial output and inflationary costs. Inflation increases along the transition in the short run from 4 to 7 percent while output falls, while output falls persistently with a maximum fall of 5.3%.

5.4.2 Subsidies for Green Production

An alternative way to accelerate the green transition is through a subsidy in the production of green energy. We investigate such transition by considering that subsidies increase along a 60 years transition from 0 in the initial steady state to 70% in the new steady state. The transition is depicted in Figure 7 with yellow dashed lines.
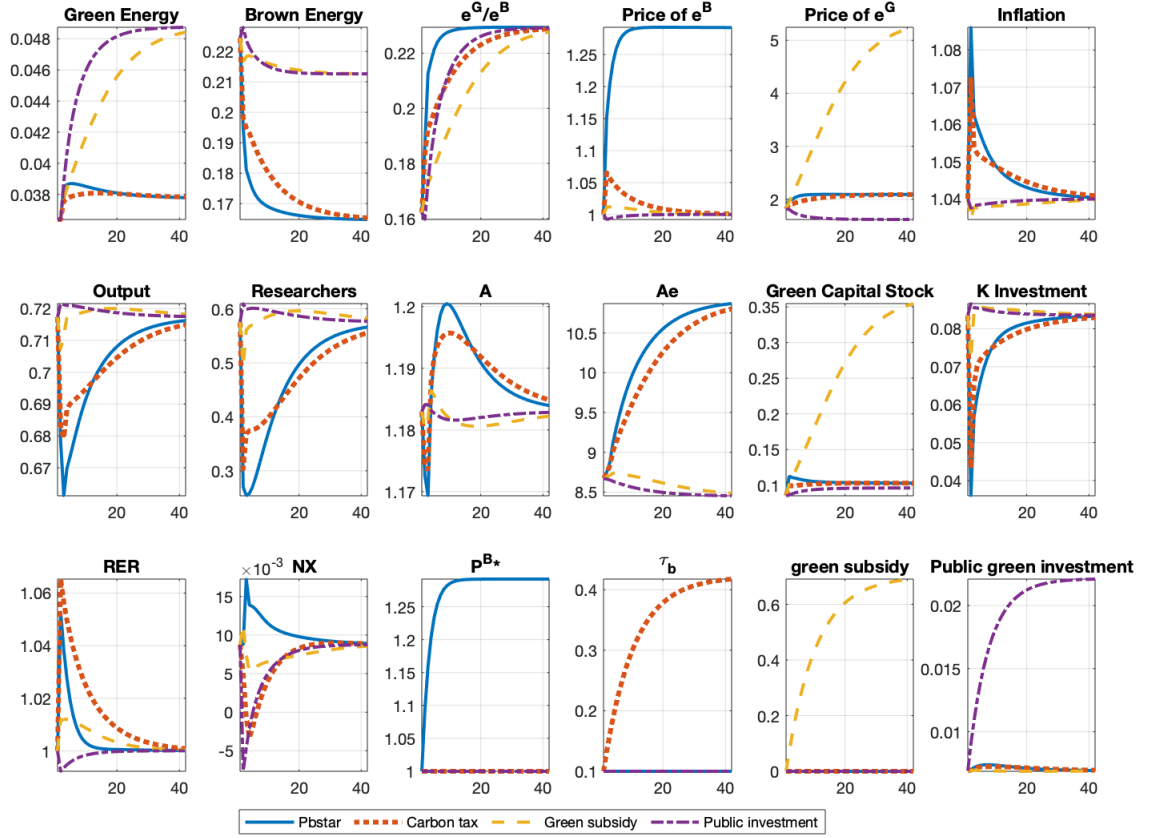
Figure 7: Transition using different fiscal instruments

The increase in subsidies generates very distinct transitional dynamics compared to the case of the increase in carbon taxes. First, with subsidies increasing firms do not feel the need to substitute brown for green energy and apart from the initial period little effort is placed in increasing the energy efficiency in production. The firms change relatively less the amount of researchers in green R&D. Given that green investments are subsidised the level of the green capital stock increases in the economy. However, the price of green energy increases since no significant advances occur in energy efficiency usage. On the other hand, since agents are Ricardian in the model they realize that the increase in subsidies will drive up future taxation and this generates a negative wealth effect that shrinks domestic demand, this results in a depreciation of the real exchange rate that increases brown energy prices. Yet, the domestic demand effect is strong enough

that balances inflationary pressures and the transition with subsidies implies small output costs but no greenflation.

5.4.3 Public green investment

The German finance minister, Christian Lindner, recently announced the launching of a 200 billion euros to fund industrial transformation between March 2022 and 2026, including climate protection, hydrogen technology and expansion of the electric vehicle charging network. At the same time, Germany is planning to boost investment in renewables for energy production. The German government, thus, intends to achieve the green transition though public investment infrastructure. In Figure 7 we plot with purple dashed-dotted lines a green transition in which public investment in green infrastructure increases by 220 percent from the initial to the new steady state.

Similarly to the case of green subsidies, the boost in green public investment generates a negative wealth effect that contracts momentarily demand, but boosts green private investment, although it provides disincentives for firms to improve on energy efficiency usage. Firms, apart from the initial period, actually allocate resources to increase the productivity of traditional factors, as the price of green energy falls in the long run. Overall, public investment encourages the usage of green energy at a lower cost without crowding out the usage of brown energy sources substantially, affecting insignificantly output and inflation dynamics.

Several comments are in order after completing this exercise: First, transitions due to increases in energy prices and taxes on brown energy are the most painful ones in terms of inflation and output losses, but at the same time they are the ones that achieve faster the desired transformation. Second, although green public investment and subsidies take longer to reach environmental objectives, they increase more effectively green energy usage but do not crowd out the usage of brown energy and they do not lead to higher efficient energy usage. Third, subsidies, push disproportionately the price of green energy and the green capital stock. Finally, when greenflation

results it is very difficult to be counteracted with subsidies or green investment and inflation deviations persist for several years along the transition.

5.4.4 Increases in brown energy prices and fiscal policy

Now, to evaluate further the role of fiscal policy along the transition, in Figure 8 we plot how the different instruments compare when the transition is induced by increases in the international price of brown energy and fiscal policy is used as an instrument to accelerate this transition. To make comparisons valid in all the exercises we assume an increase in the fiscal instrument that guarantees that the debt to GDP level returns to its steady state value in 60 periods.
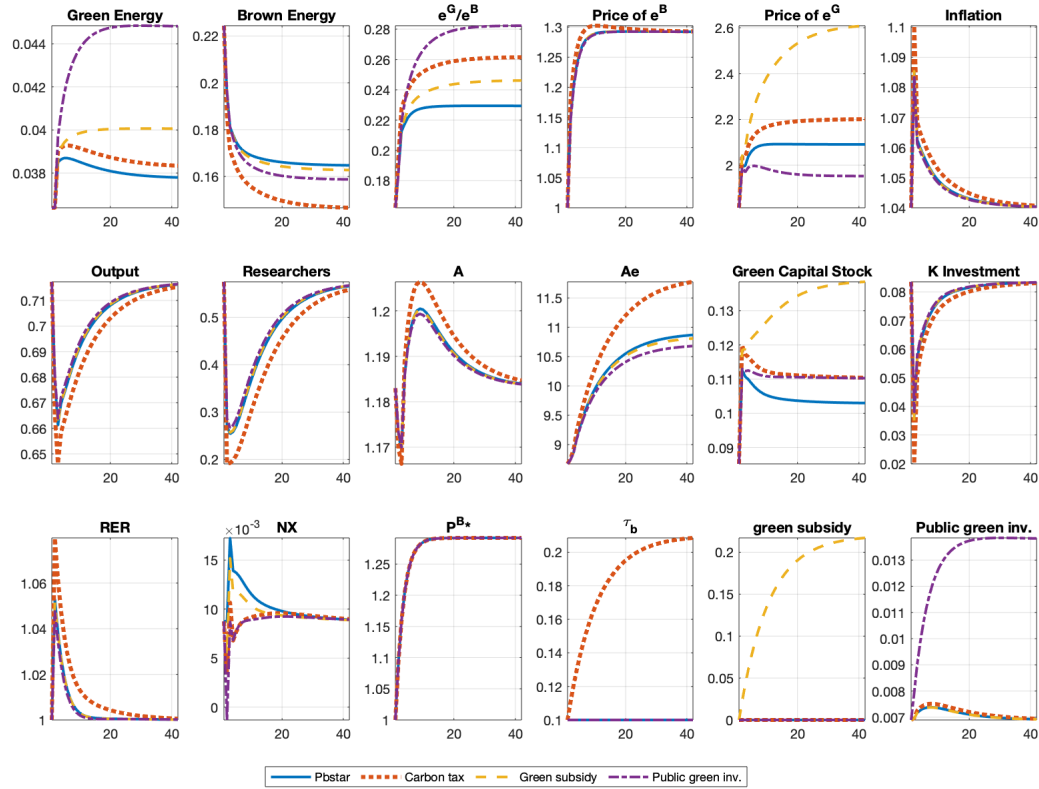

Figure 8: The role of fiscal policy along the transition

The red dotted lines in Figure 8 correspond to the case that taxes are raised from 10 to 20 percent along the transition; the yellow dashed lines to the case in which subsidies increase from 0 to 20

percent and the purple dashed-dotted lines to the case in which green investments increase by 100%.

All policies lead to a higher increase of the ratio of green to brown energy in the new steady state as depicted in the third graph of the top line of Figure 8. According to the previous analysis, carbon taxes increase further inflation and contribute to a further decrease in brown energy usage, but also imply higher output costs. On the other hand, subsidies and green investment do not affect inflationary dynamics and reduce output costs very little (almost not visible in the graph). Comparing these two last policies, public green investments lead to higher green energy usage in the new steady state and for that reason result to a higher ratio of green to brown energy in the new steady state. However, both policies do not induce a shift in more efficient energy usage. Overall, all fiscal policies consider accelerate in different degrees the green transition. Carbon taxes do more to decrease brown energy usage but at a cost of higher greenflation and higher output losses.

Given that we are interested in analyzing small open economies that are often subject to sovereign debt crisis we analyze in Figure 9 how the debt to GDP ratio and the spreads behave along the green transition when using the different fiscal instruments. The colour codes for the different transitional dynamics are the same as in the previous graphs.
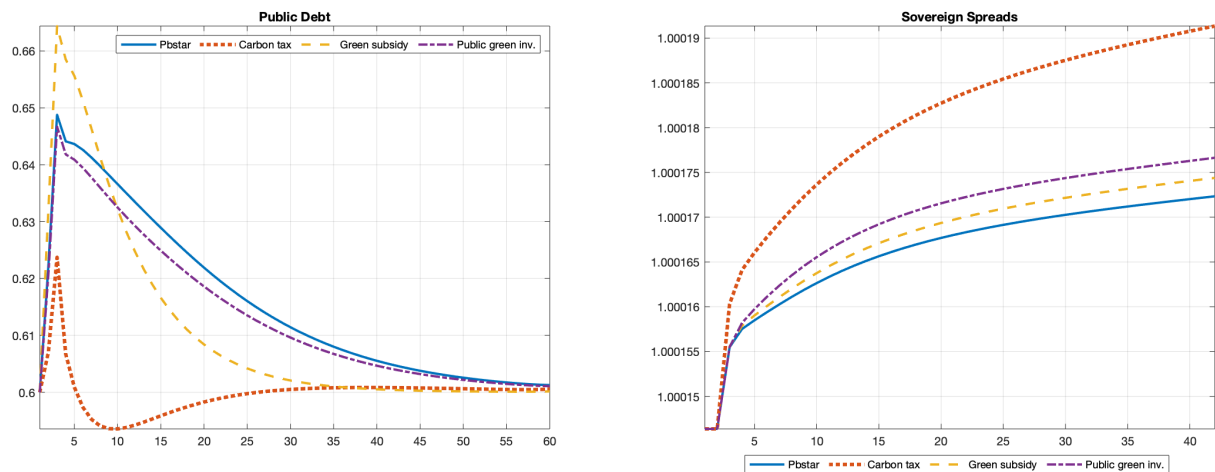

Figure 9: Fiscal burden along the transition

Although carbon taxes generate the highest greenflation they imply low fiscal costs as the simultaneous increase in the price of brown energy and carbon taxes increases fiscal revenues. Instead, subsidies are most costly for the fiscal budget. Nevertheless, the behavior of spreads reverses this picture. Given the recessionary effects of carbon taxation, international markets require higher sovereign spreads along a transition with higher carbon taxes. The spreads are lower instead when subsidies are used as the fiscal instrument along the transition.

6   The welfare costs of the green transition

The analysis we have conducted so far reveals that the green transition will be painful as it will necessarily lead to increases in inflation and output losses that persist for several periods. According to the last section, the role of fiscal policy to accelerate the transition is key, while monetary policy does not seem adequate to smooth the transition as it faces a trade off between correcting deviations of inflation and output. However, the adoption of different fiscal policy instruments entails different fiscal costs in terms of debt to GDP deviations and for the evolution of spreads along the transition. Hence, it is very difficult by looking at the inflationary and debt dynamics to conclude which policy option is the best for confronting the green transition. A natural measure to access the optimality of the different policy choices is to look at welfare. In this section, we calculate the welfare cost of the green transition under different transition scenarios. First, we recover the trend along the transitions using (13) and (14):

$$X_t = \tilde{A}_t \tilde{k}_t^\alpha X_{t-1}$$

For a given initial condition X_0, common to all scenarios. Second, we recover the path of consumption in levels along the transition:

$$c_t = \tilde{c}_t X_{t-1}$$

where $\tilde{c}_t$ is the detrended value of consumption.

We calculate the welfare using a consumption equivalence measure. We adopt as a benchmark consumption in the initial steady state and compute how much consumers are willing to give up of the initial steady state consumption in order to reach a level of welfare along the transition that is comparable to their initial steady state. :

$$W_k = \sum_{t=1}^{\infty} \beta^t ln \left(c_{t,k} + \Lambda_k \right) \tag{15}$$

where k is the correspondent scenario: 1) A 30% increase in brown energy prices, 2) increase in carbon taxes from 10% to 42%, 3) increase in green subsidies from 0% to 70%, 4) increase in Green Public Infrastructure by 220%.

The value of Λ_k determines the welfare gains or losses with respect to the initial steady state. Positive values of Λ_k imply that consumers are worse off along the transition to the new steady state compared ot the initial steady state and negative values, instead, represent welfare improvements. The first column of Table 2 presents the Λ_ks for the different scenarios considered. The green transition is associated with welfare losses as we have not included any term in the utility function that could account for factors such as health or probability of survival that would have made the transition beneficial for the model economy. Anyhow, using fiscal policy to obtain the green transition is less harmful in terms of consumption and the best fiscal instrument to obtain the green transition is clearly public infrastructure while the worst policy tool is carbon taxes. Of course, this result depends heavily on the assumption we have adopted on the production of green energy such as the substitutability between private and public green investments as well as the share of public green investments in total green energy production. So results here are sensitive to assumed parameter values for this production function. Also, the ranking of policies is also affected by the fact that we have assumed no negative externality associated with the use of brown energy.

Table 2: Welfare Comparisons

	No externality	Externality e^B	Premium $\frac{e^G}{e}$
Brown Energy price	0.079	0.180	-0.070
Carbon Tax	0.043	0.146	-0.107
Green Subsidy	0.026	0.228	-0.149
Public Infrastructure	-0.039	0.160	-0.212
Brown Energy price, ϕ_π=5	0.080	0.180	-0.069

6.1 Negative Externality

Given that our analysis concerns a small open economy, we consider that a possible externality from brown energy usage from the part of a small open economy should be minimal with respect to the global economy. In this section, we present an extension of the welfare calculations when we assume an externality derived from the utilization of brown energy in the production of domestic goods, e_t^B. We assume there exists a damage function $D\left(e_t^B\right)$ that affects household consumption in this economy. The intuition for this externality is that the pollution generated by the utilization of brown energy as an input of production generates detrimental effects on households' health, and this is reflected, for simplicity, as a fall in consumption. We follow Hassler et al. (2021) an assume the following functional form for the damages function:

$$D_t\left(e^B\right) = \tilde{\gamma}(e_t^B)^2$$

And the consumption, net of the externality is given by the following expression:

$$\hat{c}_t = c_t - D\left(e_t^B\right)$$

Following Hassler et al. (2021), we calibrate $\tilde{\gamma}$ to get the total consumption loss due to the externality, as a 20% of GDP in the initial steady state. This gives us a value $\tilde{\gamma} = 2.3326$. The second column of Table 2 presents welfare under this measure, and compares it with the baseline calculations with no assumed externality. Assuming a negative externality from the utilization of

brown energy in consumption alters significantly the welfare rankings of the different fiscal policy options. Now carbon taxes is the welfare maximizing policy option for the green transition as when carbon taxes are at place as we have seen in the previous section brown energy consumption is reduced considerably relative to the other two fiscal policy interventions. In fact, green subsidies and public infrastructure affect negatively welfare in this case as both policies do not accelerate the reduction of brown energy usage. Of course, this heavily depends on the value of $\tilde{\gamma}$. In an exercise we do not present here for economy of space we show that if we calibrate $\tilde{\gamma}$ to get the total consumption loss due to the externality, as a 5% of GDP in the initial steady state, then public infrastructure remains the best policy alternative for attaining the green transition.

6.2   Sustainability premium

When choosing between two otherwise identical products some consumers are willing to pay a higher price for a product with a reduced environmental impact. The price premium paid is typically interpreted as an indication of demand for environmental quality. A recent study conducted by global strategy and pricing consultancy Simon-Kucher Partners, reveals significant global paradigm shifts in how consumers view sustainability. [8] The study was designed to measure consumer willingness-to-pay for sustainability. According to the study's results, the sustainability premium differs across countries. In the USA for example 42 percent of consumers would be willing to pay a premium of 37 percent on sustainable products, while in Italy 38 percent of the consumers would be willing to pay but the estimated premium they would accept is only 16 percent. On average, more than a one third (34 percent) of the population is willing to pay more for sustainable products or services, and those willing to pay more would accept a 25 percent premium on average. Inspired by this evidence, we now consider that the consumption,

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[8]The Global Sustainability Study 2021 survey was conducted in July 2021, fielding through panel data provided by Dynata, an independent market research agency. The study surveyed 10,281 consumers across 17 countries.USA (N=1,062), Germany (N=1,022), Denmark (N=771), Sweden (N=757), Brazil (N=539), China (N=516), Japan (N=516), Spain (N=515), Switzerland (N=514), UK (N=513), Australia (N=510), Austria (N=510), France (N=510), the Netherlands (N=510), Norway (N=506), Italy (N=506), UAE (N=504).

when incorporating this premium is defined by:

$$\tilde{c}_t = c_t + \tilde{\gamma}\left(\frac{e_t^G}{e_t}\right) \tag{16}$$

That captures the fact that consumers have concerns about sustainability that depend on the share of green energy in total energy usage. Hence, we now interpret parameter $\tilde{\gamma}$ as the sustainability premium that enters in the utility calculations of consumers in the economy. Using the findings of the Global Sustainability Study 2021 we set $\tilde{\gamma} = 0.25$. The welfare comparisons for the different transitions appear in the last column of Table 2. The introduction of a positive externality from green energy usage in consumption renders the green transition beneficial when fiscal instruments are used to attain it. All fiscal tools increase welfare relative to the case in which brown energy increases induce the transition and again investment in public infrastructure outperforms the other fiscal measures for inducing the green transformation. As mentioned earlier, the assumed parameters of the green energy production function are key for our conclusions here. SENSITIVITY

Finally, in the last row of Table 2 we also present calculations of welfare when monetary policy reacts more strongly in inflation deviations along a transition induced by changes in energy prices. In the case of no externality and a positive premium on green energy usage fighting inflation is actually costly for welfare.

7 Short term vs. long term dynamics

Our analysis talks to the inflationary and macroeconomic dynamics along the green transition. Given that most of the existing literature studies short term dynamics in this section we present impulse responses to a transitory shock to international brown energy prices. Figure X presents the impulses of the economy to such disturbance. As for the case of the permanent shock, firms react to the shock by moving researchers to the research of more efficient energy usage to adjust in

the short run to the shock. This displacement of research, however, has persistent consequences for the efficiency of the energy use and although all variables return to their initial steady state the negative output and inflationary responses from the increase in markups reverse in the medium run. Hence, our model predictions for the short run dynamics differ, for example, from the predictions of Nakov and Pescatori (2010) who show that under standard assumptions, the effects of a positive oil price shock are identical to those of a negative productivity shock. Given that the transition is at the center of the present analysis, we discuss these issues and optimal monetary policy in our framework in an accompanying paper.

8 Conclusions

Our analysis aims at understanding the transitional dynamics of green transformation and how it interacts with fiscal and monetary policy in emerging markets. To move to a green economy we have alternative ways or a combination of them. Increases in brown energy prices and taxes decrease the usage of brown energy but do not expand the green sector, they simply improve energy efficiency use, leading to surges in inflation and output losses. Green subsidies increase the most the stock of green capital but imply a slower transition with no output and inflation costs, but higher prices for green energy. Green public investment does not enhance the stock of green capital substantially but does increase green energy usage without improving efficiency in energy use. Monetary policy can play a role in ameliorating/exacerbating greenflation in the short-run. The specific characteristics of the economy, supply or demand frictions should be taken into account when designing transitional policies as the imply different transitional dynamics and wrong choices can be very costly. talk about welfare comparisons

9 Appendix

9.1 Equilibrium equations

9.1.1 Household

$$\lambda_t = c_t^{-\sigma}$$

$$k_{t+1} = (1-\delta)k_t + i_t + \frac{\kappa_K}{2}\left(\frac{k_{t+1}}{k_t} - \bar{g}\right)^2 k_t$$

$$\lambda_t \frac{1}{P_t} = \beta\mathbb{E}_t\left[\frac{\lambda_{t+1}R_t}{P_{t+1}}\right]$$

$$\lambda_t = \beta\mathbb{E}_t\left[\lambda_{t+1}\frac{R_t^*}{\pi_t^*}\frac{rer_{t+1}}{rer_t}\Phi_{t+1}^A(\tilde{A}_{t+1}^f)\right]$$

$$\lambda_t q_t\left(1 - \kappa_K\left(\frac{k_{t+1}}{k_t} - \bar{g}\right)\right) = \beta\mathbb{E}_t\left[\lambda_{t+1}\frac{R_{t+1}^k}{P_{t+1}} + \lambda_{t+1}q_{t+1}\left(1 - \delta + \left(-\kappa_K\left(\frac{k_{t+2}}{k_{t+1}} - \bar{g}\right)\frac{k_{t+2}}{k_{t+1}} + \frac{\kappa_K}{2}\left(\frac{k_{t+2}}{k_{t+1}} - \bar{g}\right)^2\right)\right)\right]$$

$$s_{t+1}^G = (1-\delta)\, s_t^G + \Phi_s(s_{t+1}^G, s_t^G)s_t^G + i_t^G$$

$$\lambda_t q_t^G\left(1 - \kappa_S\left(\frac{s_{t+1}^G}{s_t^G} - \bar{g}\right)\right) = \beta\mathbb{E}_t\left[\lambda_{t+1}\frac{R_{t+1}^s}{P_{t+1}} + \lambda_{t+1}q_{t+1}^G\left(1 - \delta + \left(-\kappa_S\left(\frac{s_{t+2}^G}{s_{t+1}^G} - \bar{g}\right)\frac{s_{t+2}^G}{s_{t+1}^G} + \frac{\kappa_S}{2}\left(\frac{s_{t+2}^G}{s_{t+1}^G} - \bar{g}\right)^2\right)\right)\right]$$

$$\lambda_t q_t^G = \lambda_t$$

$$p_{H,t}y_{H,t} = c_t + i_t + i_t^G + i_t^{pub} + \frac{\kappa_P}{2}\left(\pi_t^H - \bar{\pi}_t^H\right)^2 p_{H,t}y_{H,t} + nx_t + p_t^B e_t^{B,*}$$

9.1.2 Intermediate goods producers

$$y_{H,i,t} = \left[\left(A_t k_{i,t}^{\alpha} \bar{h}_i^{(1-\alpha)} \right)^{\frac{\epsilon-1}{\epsilon}} + (A_{e,t} e_{i,t})^{\frac{\epsilon-1}{\epsilon}} \right]^{\frac{\epsilon}{\epsilon-1}}$$

$$e_t = \left[(1-\zeta) \left(e_t^G \right)^{\xi} + \zeta \left(e_t^B \right)^{\xi} \right]^{\frac{1}{\xi}}$$

$$r_t^k = mc_t y_{H,t}^{1/\epsilon} \left(A_t k_t^{\alpha} h^{1-\alpha} \right)^{-1/\epsilon} A_t \alpha k_t^{\alpha-1} h^{1-\alpha}$$

$$w_t = mc_t y_{H,t}^{1/\epsilon} \left(A_t k_t^{\alpha} h^{1-\alpha} \right)^{-1/\epsilon} A_t (1-\alpha) k_t^{\alpha} h^{-\alpha}$$

$$p_t^G (1-s) = mc_t y_{H,t}^{1/\epsilon} (A_{e,t} e_t)^{-1/\epsilon} A_e (1-\zeta) \left(\frac{e_t}{e_t^G} \right)^{1-\xi}$$

$$p_t^B (1+\tau^e) = mc_t y_{H,t}^{1/\epsilon} (A_{e,t} e_t)^{-1/\epsilon} A_e \zeta \left(\frac{e_t}{e_t^B} \right)^{1-\xi}$$

$$\pi_{H,t} \left(\pi_{H,t} - \bar{\pi}_H \right) = \beta \mathbb{E}_t \left[\frac{\lambda_{t+1}}{\lambda_t} \pi_{H,t+1} \left(\pi_{H,t+1} - \bar{\pi}_H \right) \frac{a_{H,t+1}}{a_{H,t}} \right] + \frac{\varepsilon_t}{\kappa_{PH}} \left(\frac{mc_t}{p_{H,t}} - \frac{\varepsilon_t - 1}{\varepsilon_t} \right)$$

$$\left(A_t k_t^{\alpha} h^{1-\alpha} \right)^{\frac{\epsilon-1}{\epsilon}} \frac{A_{t-1}}{A_t} B \phi n_t^{\phi-1} = e^{\frac{\epsilon-1}{\epsilon}} \frac{A_{t-1}^e}{A_t^e} B_e \phi \left(1 - n_t \right)^{\phi-1}$$

9.1.3 Green energy producer

$$e_t^G = \Omega L^{1-\mu} [(1-\gamma)(s_t^G)^{\omega} + \gamma(s_t^{G,P})^{\omega}]^{(\mu/\omega)}$$

$$\Omega \mu L^{1-\mu} [(1-\gamma)(s_t^G)^{\omega} + \gamma(s_t^{G,P})^{\omega}]^{(\mu/\omega)-1} (1-\gamma)\mu(s_t^G)^{\omega-1} = \frac{R_t^s}{P_t^G}$$

9.1.4 Brown energy sector

$$p_t^B = rer_t p_t^{B,*}$$

9.1.5 Government

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R} \right)^{\rho_R} \left[\left(\frac{\pi_t}{\bar{\pi}} \right)^{\phi_\pi} \left(\frac{y_t}{y} \right)^{\phi_y} \right]^{1-\rho_R}$$

$$\tau_t + \tau^e e_t^b + b_t = s p_t^G e_t^G + \frac{b_t}{\pi_t} R_{t-1} + i_t^{pub}$$

$$\tau_t - \tau^* = \phi_\tau \left(b_t - \bar{b} \right) + \sigma^\tau \epsilon_t^\tau$$

$$i_t^{pub} = \bar{I}^P$$

9.1.6   Definitions

$$1 = \left[(1 - \chi)(p_{H,t})^{1-\theta} + \chi(rer_t)^{1-\theta} \right]^{\frac{1}{1-\theta}}$$

$$nx_t = rer_t b_{t+1}^* - rer_t \frac{b_t^*}{\pi_t^*} R_{t-1}^* \Psi^A \left(\tilde{A}_t^f \right)$$

$$\pi_{H,t} = \frac{p_{H,t}}{p_{H,t-1}} \pi_t$$

$$y_{H,t} = (1 - \chi) p_{h,t}^{-\theta} \left(c_t + i_t + s_t^G + i_t^{pub} \right) + c_{H,t}^*$$

$$c_{H,t}^* = \left(\frac{P_{H,t}^*}{rer_t} \right)^{-\lambda^*} y_t^*$$

$$\frac{A_t}{A_{t-1}} = 1 + B n_t^\phi$$

$$\frac{A_{e,t}}{A_{e,t-1}} = 1 + B_e (1 - n_t)^\phi$$

$$X_t = A_t k_t^\alpha$$

$$e_t^{B,*} = e_t^B - e_t^{B,d}$$

AR(1) processes for: p_t^{B*}, μ_t^s, π_t^*, y_t^*, Ω_t, $e_t^{B,d}$.

9.2   Stationarized equilibrium equations

Define X_{t-1} as the gdp trend, and define: $g_t = \frac{X_t}{X_{t-1}}$ as the growth rate. We assume variables at t are stationarized by X_{t-1}. For instance, $\tilde{c}_t = \frac{c_t}{X_{t-1}}$.

Define: $\tilde{\lambda}_t = \frac{\lambda_t}{X_{t-1}^{-\sigma}}$.

In this section we present the stationarized equilibrium equations.

9.3 Equilibrium equations

9.3.1 Household

$$\tilde{\lambda}_t = \tilde{c}_t^{-\sigma}$$

$$g_t \tilde{k}_{t+1} = (1-\delta)\tilde{k}_t + \tilde{i}_t + \frac{\kappa_K}{2}\left(\frac{\tilde{k}_{t+1}g_t}{\tilde{k}_t} - \bar{g}\right)^2 \tilde{k}_t$$

$$\tilde{\lambda}_t = \beta g_t^{-\sigma}\mathbb{E}_t\left[\frac{\tilde{\lambda}_{t+1}R_t}{\pi_{t+1}}\right]$$

$$\tilde{\lambda}_t = \beta g_t^{-\sigma}\mathbb{E}_t\left[\tilde{\lambda}_{t+1}\frac{R_t^*}{\pi_t^*}\frac{rer_{t+1}}{rer_t}\Phi_{t+1}^A(\tilde{A}_{t+1}^f)\right]$$

$$\tilde{\lambda}_t q_t\left(1 - \kappa_K\left(\frac{\tilde{k}_{t+1}g_t}{\tilde{k}_t} - \bar{g}\right)\right) = \beta g_t^{-\sigma}\mathbb{E}_t\left[\tilde{\lambda}_{t+1}r_{t+1}^k + \tilde{\lambda}_{t+1}q_{t+1}\left(1 - \delta + \left(-\kappa_K\left(\frac{\tilde{k}_{t+2}g_{t+1}}{\tilde{k}_{t+1}} - \bar{g}\right)\frac{\tilde{k}_{t+2}g_{t+1}}{\tilde{k}_{t+1}} + \right.\right.\right.$$
$$\left.\left.\left. \frac{\kappa_K}{2}\left(\frac{\tilde{k}_{t+2}g_{t+1}}{\tilde{k}_{t+1}} - \bar{g}\right)^2\right)\right)\right]$$

$$g_t \tilde{s}_{t+1}^G = (1-\delta)\tilde{s}_t^G + \tilde{i}_t^G + \frac{\kappa_S}{2}\left(\frac{\tilde{s}_{t+1}^G g_t}{\tilde{s}_t^G} - \bar{g}\right)^2 \tilde{s}_t^G$$

$$\tilde{\lambda}_t q_t^G\left(1 - \kappa_S\left(\frac{\tilde{s}_{t+1}^G g_t}{\tilde{s}_t^G} - \bar{g}\right)\right) = \beta g_t^{-\sigma}\mathbb{E}_t\left[\tilde{\lambda}_{t+1}r_{t+1}^s + \tilde{\lambda}_{t+1}q_{t+1}^G\left(1 - \delta + \left(-\kappa_S\left(\frac{\tilde{s}_{t+2}^G g_{t+1}}{\tilde{s}_{t+1}^G} - \bar{g}\right)\frac{\tilde{s}_{t+2}^G g_{t+1}}{\tilde{s}_{t+1}^G} + \right.\right.\right.$$
$$\left.\left.\left. \frac{\kappa_S}{2}\left(\frac{\tilde{s}_{t+2}^G g_{t+1}}{\tilde{s}_{t+1}^G} - \bar{g}\right)^2\right)\right)\right]$$

$$p_{H,t}\tilde{y}_{H,t} = \tilde{c}_t + \tilde{i}_t + \tilde{i}_t^G + \tilde{i}_t^{pub} + \frac{\kappa_P}{2}\left(\pi_t^H - \bar{\pi}_t^H\right)^2 p_{H,t}\tilde{y}_{H,t} + \tilde{n}x_t + \tilde{p}_t^B e_t^{B,*}$$

9.3.2 Intermediate goods producers

$$\tilde{y}_{H,t} = \left[\left(\tilde{A}_t\tilde{k}_t^\alpha\bar{h}^{(1-\alpha)}\right)^{\frac{\epsilon-1}{\epsilon}} + \left(\tilde{A}_{e,t}\tilde{e}_t\right)^{\frac{\epsilon-1}{\epsilon}}\right]^{\frac{\epsilon}{\epsilon-1}}$$

$$\tilde{e}_t = \left[(1-\zeta)\left(\tilde{e}_t^G\right)^\xi + \zeta\left(\tilde{e}_t^B\right)^\xi\right]^{\frac{1}{\xi}}$$

$$r_t^k = mc_t \tilde{y}_{H,t}^{1/\epsilon} \left(\tilde{A}_t \tilde{k}_t^\alpha h^{1-\alpha} \right)^{-1/\epsilon} \tilde{A}_t \alpha \tilde{k}_t^{\alpha-1} h^{1-\alpha}$$

$$\tilde{w}_t = mc_t \tilde{y}_{H,t}^{1/\epsilon} \left(\tilde{A}_t \tilde{k}_t^\alpha h^{1-\alpha} \right)^{-1/\epsilon} \tilde{A}_t (1-\alpha) \tilde{k}_t^\alpha h^{-\alpha}$$

$$\tilde{p}_t^G (1-s) = mc_t \tilde{y}_{H,t}^{1/\epsilon} \left(\tilde{A}_{e,t} e_t \right)^{-1/\epsilon} \tilde{A}_{e,t} (1-\zeta) \left(\frac{\tilde{e}_t}{\tilde{e}_t^G} \right)^{1-\xi}$$

$$\tilde{p}_t^B (1+\tau^e) = mc_t \tilde{y}_{H,t}^{1/\epsilon} \left(\tilde{A}_{e,t} e_t \right)^{-1/\epsilon} \tilde{A}_{e,t} \zeta \left(\frac{\tilde{e}_t}{\tilde{e}_t^B} \right)^{1-\xi}$$

$$\pi_{H,t} \left(\pi_{H,t} - \bar{\pi}_H \right) = \beta \mathbb{E}_t \left[\frac{\lambda_{t+1}}{\lambda_t} \pi_{H,t+1} \left(\pi_{H,t+1} - \bar{\pi}_H \right) \frac{a_{H,t+1}}{a_{H,t}} \right] + \frac{\varepsilon_t}{\kappa_{PH}} \left(\frac{mc_t}{p_{H,t}} - \frac{\varepsilon_t - 1}{\varepsilon_t} \right)$$

$$\left(\tilde{A}_t \tilde{k}_t^\alpha h^{1-\alpha} \right)^{\frac{\epsilon-1}{\epsilon}} \frac{\tilde{A}_{t-1}}{\tilde{A}_t} g_{t-1}^{\alpha-1} B \phi n_t^{\phi-1} = \tilde{e}^{\frac{\epsilon-1}{\epsilon}} \frac{\tilde{A}_{t-1}^e}{\tilde{A}_t^e} g_{t-1}^{\mu-1} B_e \phi \left(1 - n_t \right)^{\phi-1}$$

9.3.3 Green energy producer

$$\tilde{e}_t^G = \Omega L^{1-\mu} [(1-\gamma)(\tilde{s}_t^G)^\omega + \gamma (\tilde{s}_t^{G,P})^\omega]^{(\mu/\omega)}$$

$$\Omega \mu L^{1-\mu} [(1-\gamma)(\tilde{s}_t^G)^\omega + \gamma (\tilde{s}_t^{G,P})^\omega]^{(\mu/\omega)-1} (1-\gamma) \mu (\tilde{s}_t^G)^{\omega-1} = \frac{r_t^s}{\tilde{p}_t^G}$$

9.3.4 Brown energy sector

$$\tilde{p}_t^B = rer_t \tilde{p}_t^{B,*}$$

9.3.5 Government

$$\frac{R_t}{R} = \left(\frac{R_{t-1}}{R} \right)^{\rho_R} \left[\left(\frac{\pi_t}{\bar{\pi}} \right)^{\phi_\pi} \left(\frac{y_t}{y} \right)^{\phi_y} \right]^{1-\rho_R}$$

$$\tilde{\tau}_t + \tau^e \tilde{e}_t^b + \tilde{b}_t g_t = s \tilde{p}_t^G \tilde{e}_t^G + \frac{\tilde{b}_t}{\pi_t} R_{t-1} + \tilde{i}_t^{pub}$$

$$\tau_t - \tau^* = \phi_\tau \left(b_t - \bar{b} \right) + \sigma^\tau \epsilon_t^\tau$$

9.3.6 Definitions

$$1 = \left[(1-\chi)(p_{H,t})^{1-\theta} + \chi (rer_t)^{1-\theta} \right]^{\frac{1}{1-\theta}}$$

$$\tilde{n}x_t = rer_t\tilde{b}^*_{t+1}g_t - rer_t\frac{\tilde{b}^*_t}{\pi^*_t}R^*_{t-1}\Psi^A\left(\tilde{A}^f_t\right)$$

$$\pi_{H,t} = \frac{p_{H,t}}{p_{H,t-1}}\pi_t$$

$$\tilde{y}_{H,t} = (1-\chi)p^{-\theta}_{h,t}\left(\tilde{c}_t + \tilde{i}_t + \tilde{s}^G_t + \tilde{i}^{pub}_t\right) + \tilde{c}^*_{H,t}$$

$$\tilde{c}^*_{H,t} = \left(\frac{p^*_{H,t}}{rer_t}\right)^{-\lambda^*}\tilde{y}^*_t$$

$$\frac{A_t}{A_{t-1}} = 1 + Bn^\phi_t$$

$$\frac{A_{e,t}}{A_{e,t-1}} = 1 + B_e(1-n_t)^\phi$$

$$g_t = \tilde{A}_t\tilde{k}^\alpha_t$$

$$\tilde{e}^{B,*}_t = \tilde{e}^B_t - \tilde{e}^{B,d}_t$$

AR(1) processes for: p^{B*}_t, μ^s_t, π^*_t, y^*_t, Ω_t, $e^{B,d}_t$, and we set $\tilde{i}^{pub}_t = 0$.

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